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A CONCENTRATOR SYSTEM FOR BI-CPVT WITH STATIC LINEAR FRESNEL LENSES

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ABSTRACT: A greenhouse with Fresnel lenses in the south facing roof and a receiver for concentrated Photovoltaic with water cooling (CPVT system) will result in electrical and thermal energy output from the solar energy excess entering a greenhouse. The PV system converts about half of the direct radiation into heat and electricity. During periods with direct radiation this will significantly reduce the heat load on the greenhouse For an optimal performance the roof elements must be asymmetric with a steep inclination at the north side (the exact angle of course depends on the latitude of the building site). The Fresnel lens structure is best oriented in upwards direction. In the current design, two lenses are placed in the inner space of a double glass. This prevents pollution and condensation on the lenses. By the upward facing of the lens structure, the focus quality is preserved over a much broader range of angles of incidence compared to a lens with downward facing structures. Each PMMA lens with a size of 1.20m x 1.52m is composed of 12 ‘tiles’ for easy production. The focal distance of the lens is 1,875m and the geometrical concentration factor is 50×. This means that in most cases the focus line is thinner than 3 cm. The performance of the lens with respect to the shape of the focal area and the position of the focal line has been analyzed with ray tracing techniques. From this analyses and by the development of a smart tracking system only two motors can bring the receivers in the required positions. One motor controls the distance between lens and receiver and the other controls the translocation of the receivers parallel to the lens. The second conclusion was that the positions of the focal line are within the bounds of the greenhouse construction for almost the whole year. Only in winter, in the early morning and at the end of the day, the focal line will be unreachable. The light sum is very stable in the greenhouse compared with the light sum outside. The 480 m^2 greenhouse, with the LCPVT system based on Static Fresnel lenses and a 12 m CPVT-module and a 200 m CT-module, is designed by Bode Project Engineering and constructed by Technokas in Bleiswijk the Netherlands. An electrical power of 37W/(m^2 greenhouse) is measured at an incoming global radiation of 870 W/m² (on a horizontal plane). The fraction collected thermal yield is about 20% of the total incident direct radiation.

Keywords: Ray Tracing, Concentrators, Energy systems, PV cells, PV module, Solar energy, Greenhouse.

1 INTRODUCTION

An important issue in greenhouses is the different needs of solar energy to the system through the year. In summer the excess of solar energy is often too large and greenhouses has to be cooled (mainly by ventilation), while in winter all energy and light can be usefully applied. A variable solar energy collector which absorbs 0 to 50% of the direct solar radiation is possible with the combination of a linear Fresnel lens and a thermal or photovoltaic module (CPVT module). A linear Fresnel lens focuses direct light onto a narrow strip. In this focal line, a photovoltaic module can convert this radiative energy into electricity. Of course this PV-module, which has to be suitable for the high radiation densities in the focal line, will become very hot so cooling is necessary. This cooling water, running from e.g. 20 °C to 40 °C, can be considered as another means to harvest solar energy, although at a relatively low temperature. The Fresnel lenses focus the direct radiation only, so the diffuse radiation, and some scattered direct radiation, passes the obstructions from the relatively tiny collectors and can be used for plant growth. In fact, the possibility of separating direct and diffuse light with the Fresnel lens,

Figure 1: Impression of the 480 m² Fresnel greenhouse with 4 roof spans with Fresnel lenses mounted at the south facing roof segments.

Figure 2: Details of the modular constructed Fresnellens. Each lens is assembled from 12 parts and two lenses are mounted in one double glass pane.

as mentioned by Jirka et al. [1] and Tripanagnostopoulos et al. [2], can be used as a special type of shading screen.In case of low light intensities (early morning, end of the day , cloudy weather and during winter), the CPVT modules can be parked aside. This means that the greenhouse has its maximal transparency. During bright

Figure 3: Details of the motor for the tracking mechanism for linear movements.

sunshine, the receiver is placed in the focus and direct light will be blocked. The thermal and electric energy from the receiver enables a large step in the construction of more energy efficient greenhouses. This investigations following more basic research performed at this field by the Greenhouse technology group of Wageningen UR [3-6].

2 MATERIALS AND METHODS

2.1 Integration in the greenhouse

Due to large efforts of Bode Project Engineering in the design stage and the accurate building of the greenhouse builder Technokas (both companies from de Lier, the Netherlands), a greenhouse was erected that supports Fresnel lenses, receivers and a sun tracking system in the roof structure. The main structure of this prototype greenhouse with a size of 480m^2 (length is 30m and the width is 16m) consists of four asymmetric roof elements (see Fig. 1 left side). Each roof element has a span of 4 m and an inclination of the south side of 30^o and on the north side of 54^o. This asymmetric roof is a result of maximizing the potential energy yield, while preventing direct light entering the greenhouse through the north facing roof (which does not have lenses), giving the ecliptics at the 52nd latitude. The spans, trellis girders, and stability bracings are made of steel. The walls of the greenhouse are covered with a 16 mm double wall polycarbonate sheet material. The span of the trellis girders is 8.00 m with two roof segments of 4.00 m. The trellis girders are 5.00 m interspaced. The ventilation windows are mounted in the north facing roofs and are implemented as windows sliding along the roof. This prevents unwanted shadows on the on the other, south oriented, roof panes with the Fresnel lenses during ventilation. In total, 25 meter of linear Fresnel lenses are mounted in every roof (the first 2.5 meter on each side of the roof are cladded with diffuse glass). The lenses have a focal distance of 1.875 m, and a geometric concentration factor of 50x. The lenses are divided in pieces of 1.20 × 1.54 m. and each such a lens is composed of 12 tiles (see Fig. 2). Two of these lenses are fitted between a double AR coated glass cladding panel. A tracking motor for the receiver movements is depicted in Fig.3. This motors are connected to gearboxes with a cogwheel rack (see Fig. 4). At each 5 m this gearbox is mounted on the trellis girders and connected with the axis of the motor. This linear movement is transferred to steel cables, which bring the

Figure 4: Details of the tracking motor (right) and the gearbox (left) of the tracking mechanism for linear movements.

receiver to the right tracking position. Each receiver is connected with two steel cables: one for the distance to the Fresnel lens and one for movements parallel to the lens.

Figure 5: Details inside the greenhouse with an overview of the cultivation area

The structure and orientation of the Fresnel lenses was optimized with ZEMAX software, as reported previously (Sonneveld, 2010). The ray tracing computer program RAYPRO, developed by Wageningen UR, was used to determine the position of the focus line for every day of the year at any time of the day. It appeared that tracking the focal line with the receiver could be performed by two motors. One motor controls the distance between lens and receiver and the other motor controls the movement parallel to the lens (and perpendicular on the groove direction).

2.2 The CPVT and CT module and tracking

Two types of receivers are applied in this greenhouse. There is 200 m of concentrated thermal collector (CT-modules. And there is 12 m of receiver with concentrated photovoltaic-cells with thermal output (CPVT -modules, see Fig. 6). The photovoltaic cells are silicon solar cells, suitable for concentration ratios up to 50×. The heat excess is removed with water cooled tubes which are laminated under the CPVT-module [7. Each CPVT receiver starts and ends with a 5 meter CT module because the first and last parts of the receiver are in the cover area without lenses. This module is the same as the other 200m of CT-receiver. The CT-receiver consists of a black painted rectangular steel profile covered with AR-coated glass with an air gap of about 7 mm. The development and testing of the new type of greenhouse with an integrated linear Fresnel lens, receiver CPVT-module and

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Figure 6: Details of the receivers inside the greenhouse with two receivers per roof

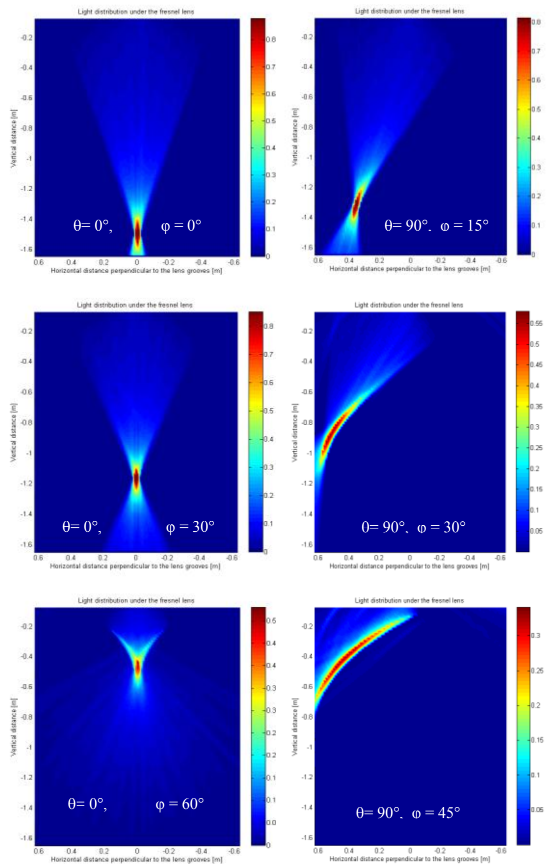

Figure 7: Intensities at the focal area for different angles of incident φ and azimuth (=0 is in line with the groves of the lens) made with Raypro ray trace simulations.

an innovative tracking system makes it possible to exploit the direct radiation in a solar energy system. Moreover, for shade tolerant plants (like ornamentals), removal of the direct radiation will drastically reduce the need for cooling and the need for screens or white wash, in summer conditions.

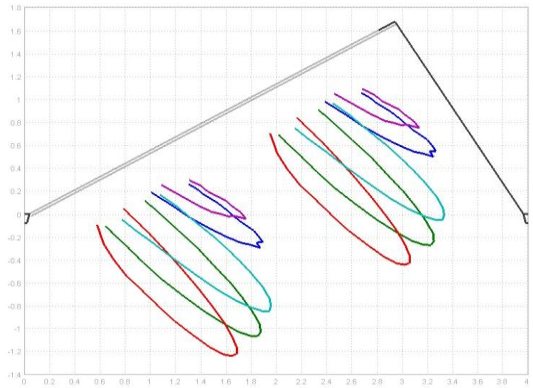

Figure 8: Trajectories of the Focal line at different times during a year. The loops each span one day course. (—— 01-03; ——01-05; ——01-07; ——01-09 and ——01-11)

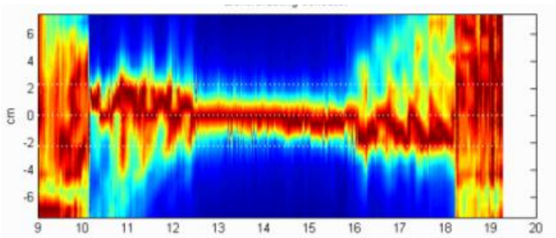

Figure 9: The intensity and width of the focal line as a function of time

3 RESULTS AND DISCUSSION

3.1 Measurement of the yield of the system

A selection of the results of the ray tracing program which determines the position of the focus line as a function of the angle of incidence, are presented in Fig. 7. The angle of incidence (φ) is defined from a line perpendicular to the lens surface, and the azimuthal angle (θ) is defined from the direction of the focal line (which is the same as the grove direction). In the graphs, the shortening of the distance between the focal line to the Fresnel lens can be noticed at increasing angles of incidence at an azimuth angle zero (radiation from the direction of the grooves). In the situation of azimuth angle 90° (so perpendicular to the grooves), the focal line moves with the angle of incident according to the Figs. 7d, e, f. At higher angles of incidence the focal area spreads out to larger areas. In these situations there is a large area instead of a small spot where the collector could be placed to receive a line of light. This means that the ray tracing software was used to find the optimal place, based on a selection from possible locations. This exercise resulted in pathways for the receiver as presented in Fig. 8. The knowledge on the course of the (optimal) focal line during the day is used for an automated positioning of the receiver for each moment of the day. In addition to this, a fine tuning of the receiver position is performed by a feedback signal from a light responsive diode array which measures the light intensity in a 0.75 cm linear grid, perpendicular to the receiver. Fig. 9 shows the result from this diode array. A dark, narrow line in the center of the graph indicates a sharp intensity in the focal line. Between 10:00 and 12:30 and between 16:00 and 18:00, the dark region in the graph gets more blurry. This is the consequence of less a sharp focus line as could be seen in Fig. 8 at the less favorable angles of incidence (the three graphs at the right side).

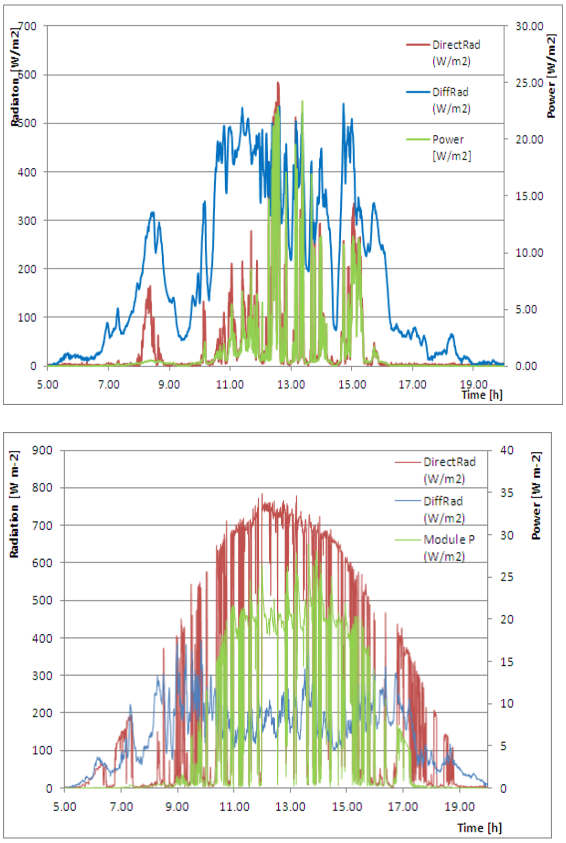

Figure 10: The generated electric power (Power) and direct and diffuse radiation (Radiation) as a function of time on top: cloudy day August 6th, and bottom: bright day August 7th, 2011

3.2 Performance of the CPVT system

The performance of the CPVT system with linear PMMA Fresnel lens was determined with practical measurements. In Fig. 9 the light intensity and width of the focal line is given for a clear day: 3th May 2011. An overview of the solar radiation and the electrical energy yield on a cloudy day (August the 6th) and a bright day (august the 7th) is given in Fig. 10 respectively top and bottom. For Dutch climate conditions, a peak power of approximately 30 W/(m² greenhouse) electrical output can be expected at a maximal global radiation of 870 W/m^2. The yearly electricity production is expected to be almost 20 kWh/(m² greenhouse) and the thermal yield on 110 kWh/(m^2 greenhouse). The average collected thermal yield and direct global radiation as function of time is given in Fig. 11. The fraction collected thermal yield is about 20% of the total incident direct radiation. Measuring daily the light sum (Fig. 12) result in a very stable light sum in the greenhouse compared with the light sum outside.

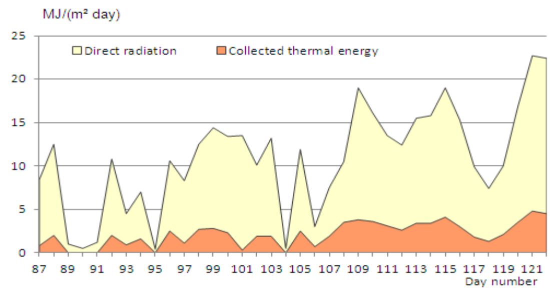

Figure 11: Incident direct radiation and amount of collected thermal energy in 2011.

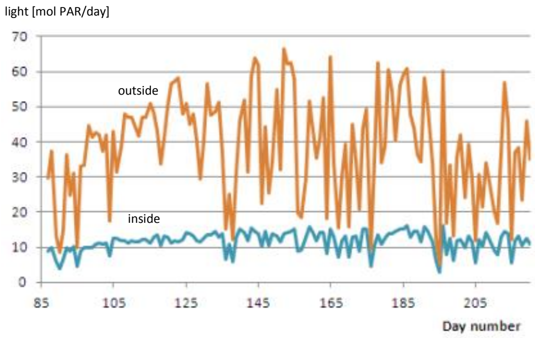

Figure 12: Light sum in- and outside the greenhouse 2011.

4 CONCLUSIONS

A 480m^2 greenhouse with a CPVT system based on Static Fresnel lenses and both 40 m CPVT-module and a 200 m CT-module is constructed in Bleiswijk, the Netherlands. The greenhouse construction is characterized by a asymmetric roof with a south facing roof with a slope of 30^o and a smaller north facing roof with a slope of 54^o. The south facing panes contain two lenses, made from PMMA. The focal distance of the lens is 1,875m and the geometric concentration factor 50×. In most cases, the focus line is thinner than 3 cm.

The performance of these lenses has been analyzed with ray tracing techniques with respect of the shape of the focal area and the position of the focal line. From this analyses it was concluded that tracking of the receiver module is possible with two motors. One motor controls the distance between lens and receiver and the other motor controls the movement parallel to the lens (and perpendicular to the groove direction). The second conclusion was that the positions of the focal line will be within the bounds of the greenhouse for most of the year. Only in winter, in the early morning and at the end of the day, the receiver will not be able to reach the focal line, which is considered to be no problem because of the low intensities in those periods. The light sum is very stable in the greenhouse compared with the light sum outside. An electrical power of 30W/(m^2 greenhouse) is measured at an incoming global radiation of 870 W/m² (on a horizontal plane). The fraction collected thermal yield is about 20% of the total incident direct radiation.

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